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DESIGN OF LANTHANIDE MAGNETOSTRICTIVE SONAR PROJECTORS

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ABSTRACT

The interest of Rare Earth-Iron magnetostrictive transducers for low frequency sonar is shown by the measurement results of the Quadripode II **Tonpilz** prototype : high acoustic power of 1.6kW in a compact size, large bandwidth and a good reliability. These results are well explained by means of modelling which reveals a particularly high elastic energy density. Recent measurements results on a test transducer have shown that this energy density can still be highly increased which will be applied on a new version of the Quadripode. Assuming also the same properties for Terfenol-D, a new prototype, a compact **double ended vibrator**, has been computed, aiming more severe specifications : lower frequency, higher acoustic power, permanent magnet bias. Concepts used to design this transducer as well as the computed performances are presented. This prototype is an intermediate stage before to design **Flextensional** transducers for 'low-low' frequency sonar.

INTRODUCTION

Because with low frequency propagation conditions are better and sonar range is increased, the trend in transmitting transducers is to lower the resonance frequency [1]. Until now, piezoelectric Tonpilz-type transducers have given satisfaction, but with the new desired range of frequencies, their size is becoming a major problem.
The first way to deal with such a problem has been to study other types of mechano-acoustic conversion principle such as Flextensional types [2]. However, even if the frequencies aimed at have been reached, all the technological problems are not solved (shell aging for example). Moreover, the transducers may be still very bulky in the case of very low frequencies ('low-low frequencies').
Another way of research is to retain (temporarily) the conventional design concepts and to take a new active material, more suited to the aim. This opportunity is offered by the attractive properties of magnetostrictive rare earth-iron alloys, especially the Terbium-Dysprosium-Iron alloy, discovered by A.E.Clark and called Terfenol-D [3]. This alloy displays a 'giant magnetostriction' (between 1000 and 2000 ppm), a low Young's modulus and a good electromechanical coupling factor.
Previous works have already proved that use of Terfenol-D instead of ceramics leads to a significant decrease of the resonant frequency [4].

A first french prototype, a Tonpilz-type named the Quadripode [5], has permitted to prove that a significant acoustic power can be produced using Terfenol-D: The level of 1 kW has been reached in 1988 [6]. Since this success, intensive researches [7] have been undertaken in different ways: Characterization of Terfenol-D [8], development of new mathematical models such as 3D-electroacoustic FEM [9,10], design of new magnetic circuits [11], improvement and new design of transducers [12].

The purpose of this paper is to present all the results obtained on transducers since 1988 [6]: Characterization of different Terfenol-D alloys has led to an improved version of the Quadripode, called the Quadripode II, which will be compared to the first version. Recent measurements results [13,14] on a test transducer have shown that the power of this transducer can still be highly increased by a better use of Terfenol-D, which could be applied on a new version of the Quadripode. A low-frequency double ended vibrator, considered as an intermediate stage before the Flextensional transducer, has been designed, giving a compact structure with a very high figure of merit.

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NEW DEVELOPMENTS IN TONPILZ TRANSDUCERS

The Tonpilz structure has been studied at first because it is a rather well understood structure. It permits to concentrate research efforts on the way to use the active material.

The Quadripode transducer is a Tonpilz, the active elements of which are four 18mm-diameter by 100mm-length rods of Terfenol-D (figure 1). The description of its structure being done elsewhere [5,6,7], only the last measurements results are given here.

The first version of this transducer has been realized in 1987 using a french laboratory Random Oriented (R.O.) Terfenol-D. In spite of the small amount of active material used (about 100 cm^3), it has reached a 1kW acoustic power (table 1). Its has permitted to show the ability of Terfenol-D to produce a significantly high power and to show that technological problems due to the use of Terfenol-D has solutions. The cooling device in particular appeared rather reliable and quite satisfactory. It permits to use the transducer during several hours with a high working rate (20%) and without any change of behaviour.

In 1988, Terfenol-D became commercially available which permitted to undertake characterization of alloys coming from all the world producers. It showed that Grain Oriented (G.O.) alloys are much more suited to sonar transducers. As the coupling factor is between 60% and 70% instead of 30% for R.O. alloy, a significant increase of acoustic power of the Quadripode was expected if G.O. alloys were used instead of R.O. alloys. This was the basic idea of a second version of the Quadripode, named Quadripode II.

The second version of the Quadripode has been realized in 1988 and tested in 1989. Apart the head mass and the pre-stress rod which is strenghened and the Terfenol-D rods which is changed, the two transducers are identical. As expected, its acoustic power is increased significantly (Table 1). Because the G.O. alloy is more compliant than the R.O. alloy [7,8] the resonant frequency of Quadripode II is a bit lower than that of the Quadripode I. As a consequence the directivity index of the Quadripode II is a bit lower than that of the Quadripode I and thus the maximum source level is only 1 dB higher. The mechanical quality factor is divided by two, leading to a very wide passband (Figure 2). The overvoltage factor (the ratio of the imaginary part of the impedance to the real part of the impedance) is 2 instead of 6 which means that the effective coupling factor is much better. At least, the efficiency appears independent of the Terfenol-D nature, staying rather low. Present works are under progress to look how to improve this point.

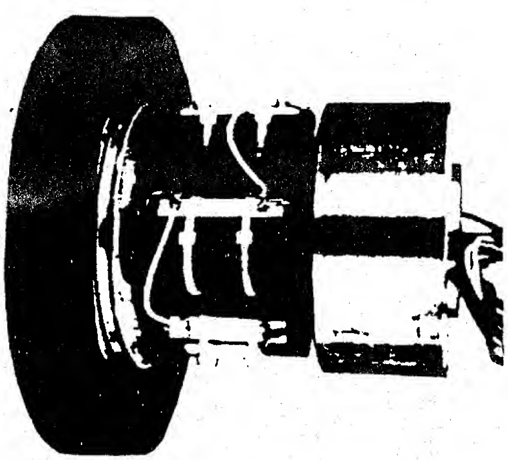


Figure 1 : The Quadripode transducer without its case and its cooling device

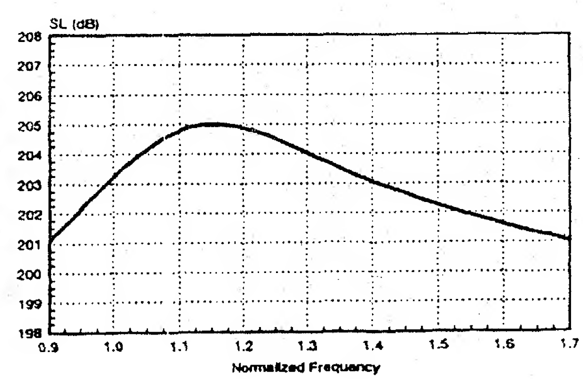


Figure 2 : Quadripode II Sound level versus arbitrarily-normalized frequency

QUADRIPODE		I	II
Series resistance	R_s (Ohm)	10	27
Series inductance	L_s (mH)	8	7
Overvoltage factor	Q_e	6	2
Mechanical quality factor	Q_m	5	2.5
Effective coupling factor	k_{eff} (%)	20	50
AC-Efficiency	e_{ea} (%)	25	25
Transmitting voltage response	TVR (dB)	142	145
Transmitting current response	TCR (dB)	178	180
Directivity index	D (dB)	3.0	2.2
Excitation current	I (A_{rms})	20	17
Excitation voltage	U (kV_{rms})	1.2	1.0
Acoustic power	P_a (kW)	1.0	1.6
Total efficiency (AC+DC)	e_t (%)	15	15
Sound level	SL (dB)	204	205

Table 1 :Quadripodes performances at maximal level (Reference for acoustic levels is 1μPa @ 1m)

Thanks to theoretical models, it is possible to analyse fields inside the magnetostrictive rods. It appears that to get a good agreement between measurement (electric impedance, acoustic level) and computation, a giant dynamic strain should necessarily exist. At resonance, the stress amplitude is equal to the pre-stress value (31 MPa) and the peak-to-peak strain amplitude appears to be equal to 1960 ppm, which is higher than the static strain at saturation measured on the Terfenol-D rods [7].

This result has led to suppose that it is possible to get dynamic peak-to-peak strains amplitudes much higher than static magnetostrain. This has been checked [13,14] by measurements on a test transducer excited at high level, prestressed at 43 MPa and biased at 160 kA/m. At resonance, the maximum amplitude has been found equal to 2440 ppm (Figure 3), so about 50% higher than the typical maximum static strain (1600ppm) in the same pre-stress conditions. Like with the Quadripode, the transducer limit is reached when the stress amplitude is equal to the pre-stress. But as the pre-stress is higher in the test transducer, the maximum strain obtained is higher also. In the same way, a peak-to-peak strain amplitude of about 4000 ppm could theoretically be reached at resonance using a 65MPa pre-stress and both a high bias and a high excitation level. In terms of elastic energy density, it means that 22.3 kJ/m^3 have been reached experimentally instead of the 9.6 kJ/m^3 obtained considering that the maximum peak-to-peak strain is equal to the saturation static strain.

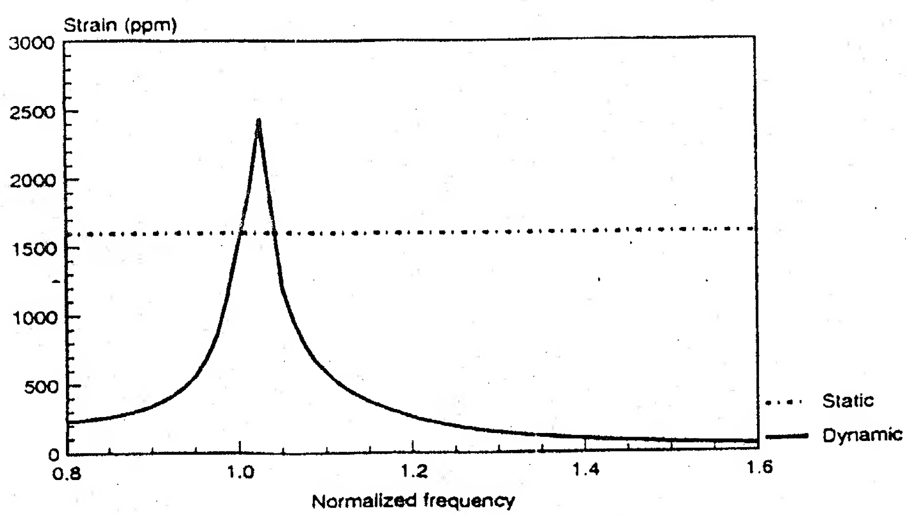
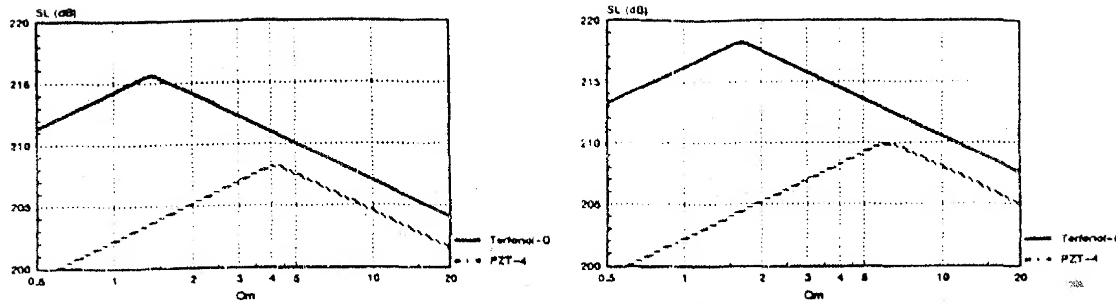


Figure 3 : Peak-to-peak strain amplitude of Terfenol-D in a transducer versus normalized frequency, compared to the typical value of maximum static strain at the same pre-stress.



Case 1 : T_o = 43 MPa, H_o = 160 kA/m   Case 2 : T_o = 65 MPa, H_o = 200 kA/m

Figure 4 : Comparison on the Sound Level between Terfenol–D and PZT transducers versus the mechanical quality factor Q_m in two cases of prestress T_o and bias H_o.

The main consequence for transducer design as regard this important result is that the acoustic power limit is prescribed only by the pre–stress and the bias field. Taking this result into account, a new comparison between Terfenol–D and PZT–4 can be done on transducers, using the same features than Moffett et al [15]: Resonant frequency in water = 500 Hz ; Active material volume = 1000 cm^3 ; Electromechanical efficiency = 50% ; Directivity Index = 0 dB ; Mechanical Quality factor considered as a parameter.
The acoustic power is calculated using classical formula taking into account field and stress limitations. In the case of PZT–4, the electric field limit is equal to 557 kV/m, while in the case of Terfenol–D, the magnetic field is limited by the bias field. In both cases, the stress limit is given by the pre–stress.The comparison between Terfenol–D and PZT is done on the Sound Level which depends simply on the acoustic power (Figure 4). Thanks to the possibility to use high bias and high pre–stress, Terfenol–D leads to more powerful transducers than PZT–4 whatever the Q_m value is. For low Q_m values, like those encountered in antenna, Terfenol–D transducers are between 10 and 20 times more powerful than PZT transducers.

This result could be also applied on the Quadripode transducer, leading to a new Quadripode version. According to theoretical calculations, a change of pre–stress from 31 MPa to 43 MPa would permit to double the power and to increase the acoustic power higher than 3kW. In order to compare the Quadripode transducers to piezoelectric transducers, criterion such as the Figure of Merit in Volume FM_V can be introduced :

$$FM_V = P_a/(Q_m.F_o.V_T)$$

where P_a is the acoustic power, Q_m is the mechanical quality factor in water, F_o is the resonant frequency in water, and V_T is the transducer volume. It is a good way to evaluate the transducers miniaturization. According to this criterion, the Quadripode transducer is superior to a typical GERDSM piezoelectric transducer of the same frequency and same size (Table 2).

-		P_a (kW)	Q_m	M (kg)	V_T (dm^3)	FM_V
Tonpilz type						
PZT–4	GERDSM	2.6	9.0	70	10.0	2.8
Terfenol–D	Quadripode I	1.0	5.0	75	5.1	3.1
	Quadripode II	1.6	2.5	77	5.1	10.5
	New Quadripode	3.1	2.5	77	5.1	20.6
Double–ended type						
PZT–4	GERDSM	0.3	3.0	80	11.5	1.7
Terfenol–D	New Janus	3.3	5.0	130	8.4	15.7

Table 2 : Comparison between PZT and Terfenol–D transducers of different types.

NEW TRANSDUCERS

In order to work at lower frequencies than Tonpilz frequencies, other mechano-acoustic principles are studied, using Terfenol-D drive elements.

As the double-ended vibrator is a simple means that can satisfied this goal, it has been studied at first. Using different modelling tools, a transducer called Janus has been obtained (figure 5). It is very compact as regard its performances (Table 2) and its resonant frequency in water : Twice less than that of the Quadripode II.
This transducer is based on four drive elements. Each of these elements is composed of a 20mm-diameter 200mm-length Terfenol-D rods, surrounded by a permanent magnet for the bias, the principle of which is not described here. Around this magnet, is the coil. In order to reduce the dynamic magnetic energy of the return path, a magnetic circuit has been designed according to the 'open magnetic circuit concept' [11] : The magnetic field does a loop through the air (figure 6). Thanks to the magnetic pole pieces at the ends of the rod, which spread the flux from the rod to the air, almost all the magnetic energy is concentrated in the rod. This principle has been checked by modelling using ATILA and FLUX2D softwares as well as by measurements [7].
The head mass diameter is 400 mm, which is rather small compared to the wave length. Like in the Quadripode, there is a forced cooling device. Finally a transducer contained in a 500mm x 420mm x 410 mm box is obtained.

Compared with a GERDSM PZT transducer (Table 2) which uses the same amount of active material and which has the same resonant frequency, the Terfenol-D Janus provides much more acoustic power (3.3kW, 10 factor improvement). This result confirms the ability of Terfenol-D to provide low-frequency high-power sonar sources. It should be emphasized as a technical advantage that this type of transducer could be realized from now without any difficulty.

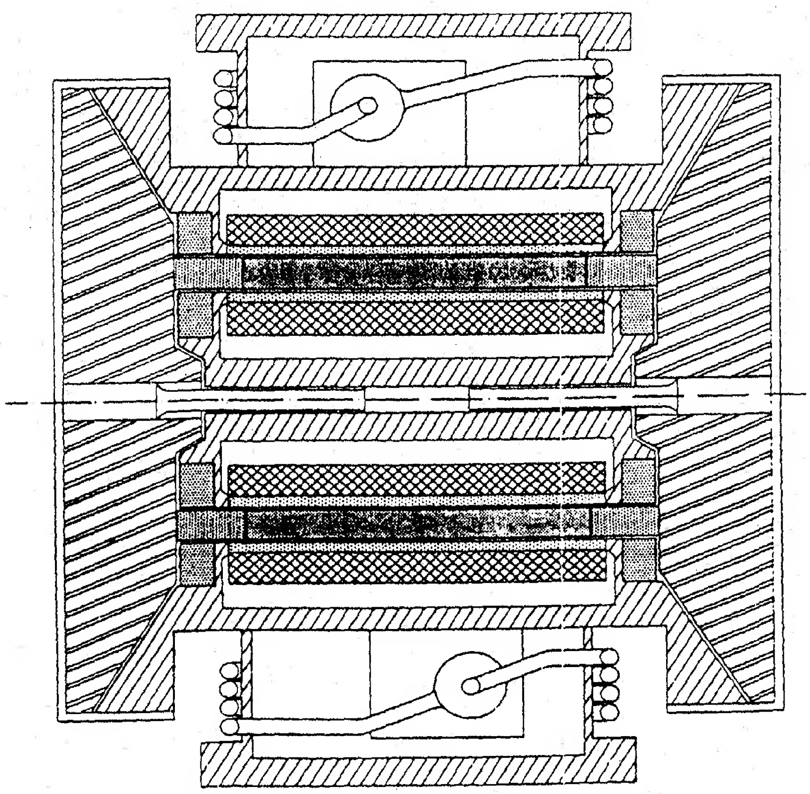


Figure 5 : Scheme of a low-frequency double-ended vibrator called Janus

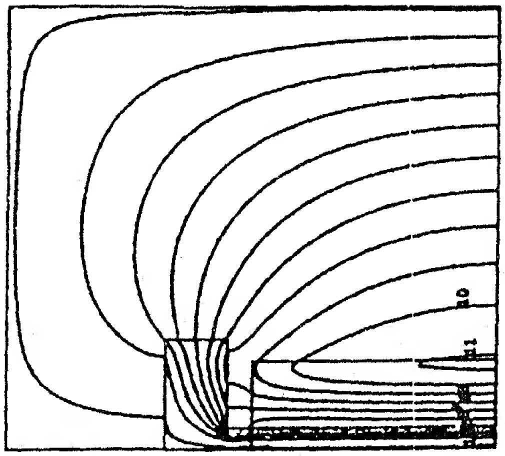


Figure 6 : Magnetic lines distribution in the open magnetic circuit concept
(Computation with FLUX2D on half a rod, taking into account axial symmetry).

A more complex means to realize a very low frequency source is to use the mechanoacoustic conversion of the Flextensional type.

This principle should lead a priori to the must compact transducer on condition to solve several mechanical problems. In addition to those already encountered in PZT types, there are new problems related to the use of Terfenol-D drive elements. These drive elements are shorter than PZT stacks but much more thicker. Due to this difference of geometry, it is not possible to take a good PZT Flextensional and to exchange its PZT stacks against Terfenol-D drive elements to get an efficient transducer. An extensive work has to be done to design a shell well suited to the Terfenol-D drive elements. Note at last that as the strains due to Terfenol-D are much larger than those of PZT, shell aging will be increased.
Research has begun to design a Flextensional working at a frequency 4 times less than that of the Quadripode. FLUX2D and FLUX3D CAD softwares are used to design magnetic circuits, permanent magnet biasing, eddy currents effects. ATILA code is used to design the shell and to look at the 3D electro-acoustical behaviour of the whole transducer [10].

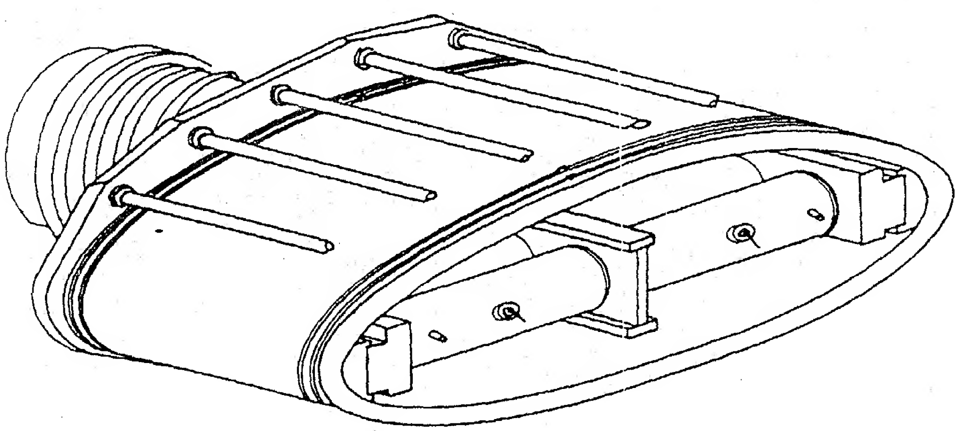


Figure 7 : Scheme of a very low-frequency Flextensional transducer.

CONCLUSION

Research on Lanthanide magnetostrictive sonar projectors begins to give effective results : The Quadripode, a low-frequency Tonpilz transducer using a small amount of Terfenol-D, provides an acoustic power higher than 1.6 kW and a wide passband. According to the figure of merit criterion, it appears already better than many comparable PZT transducers.
Research on the limits of Terfenol-D transducers has shown that at resonance, the peak-to-peak strain amplitude can be much higher than the static saturation strain (1600ppm). For example, a 2440 ppm strain amplitude has been measured. As a transducer at resonance is limited only by magnetic field and stress, the use of high bias and prestress permits to get very high elastic energy density in Terfenol-D.
This result have direct consequences on the transducer design. It leads to the superiority of Terfenol-D transducers on PZT transducers whatever the mechanical quality factor is. It could lead to an improved version of the Quadripode, able to provide 3kW acoustic power.
Research on new transducers are under progress. The double-ended transducer, named Janus, is an attractive solution to realize low-frequency sonar source. At the opposite of the Flextensional type which presents the largest potential but which is complex to design, this transducer could be realized from now without any difficulty.

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ACKNOWLEDGEMENT

The authors thank DRET G24 (French Ministry of Defence) to have supported a part of these works [13,14].